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ALGAE-BASED JET FUEL: THE RENEWABLE ALTERNATIVE TO THE AIR FORCE'S FOCUS ON COAL-TO-LIQUID SYNTHETIC FUEL

by

Thomas P. Seymour, Maj, USAF

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Instructor: Colonel Fred Stone

Maxwell Air Force Base, Alabama

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Abstract

In his 2006 State of the Union Address, President George W. Bush established a national goal to replace 75 percent of U.S. oil imports by the year 2025. As the single largest consumer of energy within the Department of Defense, the USAF embraced the President's goal and began to reduce dependence on foreign oil through a strategy of energy conservation and the development of oil alternatives. The Air Force established a goal to acquire 50 percent of its domestic aviation fuel requirement by the year 2016 via domestically-sourced alternative fuel blend. To date, this initiative's focus has revolved around establishing a domestic coal-to-liquid (CTL) fuel industry with enough capacity to meet Air Force needs. However, technical, environmental and political realities have changed such that the Air Force should consider changing its focus on CTL jet fuel.

This paper examined current realities to determine whether the Air Force should abandon initiatives that encourage a domestic CTL fuel industry and instead concentrate research, development and incentives toward acquiring renewable jet fuel derived from algae in order to stay on track toward its 2016 goal. Renewable fuels produced from algae are an attractive solution to the Air Force's alternative aviation fuel goal. The results showed that neither CTL fuel nor algae-based jet fuel are likely to be commercially viable in time to meet the Air Force's 2016 goal. However, a recent shift in national energy policy requires the Air Force to change its focus to algae-based jet fuel in order to align the initiative with national policy and posture for future success.

Introduction

In the past two decades, the United State's reliance on foreign oil has nearly doubled. In 1988 the United States imported 38 percent of its crude oil. For the last four years, it has annually imported more than 66 percent of its crude oil.[1] While the nation's reliance on foreign oil has peaked over the past four years, the volatility of oil prices exposed the danger of oil dependence. During the same time period, a barrel of crude oil initially sold for $42 in January 2005. Within a year the price increased nearly 50 percent to $63 per barrel. By July 2008, the price sky rocketed to $142 per barrel of oil.[2] Realizing the implications of foreign oil dependency on both U.S. national security and the economy, President George W. Bush announced in his 2006 State of the Union Address, "Keeping America competitive requires affordable energy. And here we have a serious problem: America is addicted to oil, which is often imported from unstable parts of the world."[3] President Bush then established a goal to "…replace more than 75 percent of our oil imports from the Middle East by 2025." President Bush focused on energy independence and eliminating the nation's reliance on Middle Eastern regimes, some of which are unfriendly toward the United States. According to President Bush, one of the keys to reaching this goal is to change the way the United States powers its transportation sector by increasing the production of alternative fuels, among other initiatives.[4] The Department of Defense (DOD) and the United States Air Force (USAF) took notice.

As a whole, the DOD accounts for nearly two percent of U.S. oil consumption with the USAF requiring 57 percent of this total.[5] Similar to President Bush's desire for affordable American energy, the USAF has a keen interest in inexpensive and stable fuel prices. In 2007, the USAF spent nearly $6 billion on fuel, up from $2 billion in 2003.[6]

The volatility of oil prices also wreaks havoc on the Air Force budget. With every $10 increase in the price of a barrel of oil, the USAF must adjust its budget to find an additional $600 million for fuel.[7] As the single largest consumer of oil within the DOD, the USAF embraced the President's goal and began to reduce its oil dependence through a strategy of energy conservation and the development of oil alternatives.[8] One of the major goals of the Air Force's alternative fuel initiative is to acquire 50 percent of the Air Force's domestic aviation fuel requirement by 2016 via a domestically-sourced alternative fuel blend.[9] To date, the Air Force has focused on synthetic jet fuel produced using the Fischer-Tropsch (FT) gasification process because it not only offers a technologically mature alternative to petroleum, but also a domestic source of alternative fuel with which the Air Force could meet its 2016 goal. Because the United States has coal reserves estimated to last over 200 years, FT coal-to-liquid (CTL) fuel appears to offer the best solution to the Air Force's alternative fuel goals.[10] However, much has changed since President Bush announced his goal to wean the nation off of foreign oil in early 2006.

A significant change has occurred in the political landscape with an ensuing shift in policies. Following the 2006 and 2008 elections, the national energy discussion transitioned from one about gaining oil independence to one focused on climate friendly and renewable energy. Recently, in an address to a Joint Session of Congress, President Barack Obama anchored this discussion when he said, "We know the country that harnesses the power of clean, renewable energy will lead the 21st century…. to truly transform our economy, protect our security, and save our planet from the ravages of climate change, we need to ultimately make clean, renewable energy the profitable kind of energy."[11] One such form of energy is renewable fuel derived from algae. The production of algae-derived jet fuel promises to be an affordable, environmentally friendly and renewable solution to meet Air Force alternative fuel goals. This paper examines current realities and determines whether the Air Force should now abandon initiatives that encourage a domestic CTL fuel industry and instead concentrate research, development and incentives toward acquiring renewable jet fuel derived from algae in order to stay on track toward its 2016 goal.

In order to argue this thesis, the paper uses the evaluation framework. Using this framework, the paper assesses how well FT CTL fuel and algae-derived fuel will facilitate the Air Force's 2016 alternative fuel goal.

The paper begins by providing background information on the USAF alternative fuels initiative and the two fuels being evaluated. After discussing the history of the USAF alternative fuel initiative, the paper discusses the FT CTL alternative, the history of FT fuel and the process of turning coal into jet fuel. Next, the paper covers algae-derived fuels, the history of algae fuel research and the algae fuel production process. The paper then transitions to address why no other feasible alternative jet fuel exists with which to meet the USAF 2016 alternative fuel goal. Lastly, the background section ends with a literature review to discuss what other researchers have argued with respect to this thesis.

Once the paper has provided sufficient background, the argument proceeds by establishing the evaluation criteria applied to assess the ability of FT CTL fuels and algae-based fuels to meet the USAF 2016 alternative fuel goal. The key issues used to determine the criteria are inherent to the USAF 2016 goal. The Air Force plans to "*cost* *competitively* acquire *50 percent of the Air Force's domestic aviation fuel requirement* via an alternative fuel blend in which the alternative component is *derived from domestic sources* produced in a manner that is *greener than fuels produced from conventional petroleum*."[12] With these key issues identified, the evaluation assesses, by 2016, each fuel's: 1) technical readiness to produce sufficient quantities of fuel using domestic resources and its ability to substitute for petroleum jet fuel; 2) ability to be economically viable and compete with petroleum fuels; 3) environmental impact associated with using each fuel; and 4) political considerations that may affect research, development and large-scale production.

After defining the evaluation criteria, the argument proceeds to the results of the evaluation and the analysis of results. The argument focuses on each alternative fuel and how well it meets the criteria. The paper then analyzes the results. The analysis determines which alternative fuel is better suited to meet the USAF 2016 goal. The argument then moves to recommendations and the conclusion.

The final section of the paper offers recommendations and summarizes the research with a conclusion. Derived from the research, the recommendations provide Congress, the DOD, and the USAF suggested investments and policy changes that will facilitate reaching the USAF 2016 alternative fuel goal.

Background

By seeking oil alternatives, the Air Force hopes to promote energy security for the nation and stabilize its rising fuel costs. Even before President Bush gave his 2006 State of the Union Address, the Air Force was thinking about alternative forms of energy. In late 2005, Secretary of the Air Force Michael Wynne established an 11-member panel to investigate which alternative fuels may be useful to the Air Force.[13] Thereafter, the Air Force began a program to test FT fuel in Air Force aircraft with a purchase of 100,000 gallons of natural gas-to-liquid FT fuel from Syntroleum, a U.S.-based company.[14] The Air Force chose the B-52H as the first platform to test the synthetic fuel.

In order to coordinate B-52H synthetic fuel test and certification activities, the USAF established the Alternative Fuels Certification Office (AFCO). The AFCO, combined with the Air Force Research Lab (AFRL), began work to certify the B-52H for synthetic fuel use. Early in the certification process, the AFRL discovered a considerable drawback of synthetic fuels when used in jet engines. Unlike petroleum fuels, synthetic fuels are significantly cleaner, contain almost no sulfur and lack complex chemicals known as aromatics.[15] The aromatics in petroleum fuels react with aircraft rubber seals causing them to expand. Without aromatics, aircraft seals don't expand and aircraft fuel systems leak.[16] According to an engineer within the AFRL fuels and energy branch, "[AFRL] ran a 100 percent FT fuel test on an [aircraft] and let it sit overnight. When we came back the next morning fuel was leaking out of the plane."[17] In order to address this shortcoming, the AFRL blended synthetic and petroleum fuel together in a 50/50 ratio. The synthetic fuel blend incorporates enough aromatics to properly seal aircraft fuel systems. "After we drained the aircraft and refueled it with a 50/50 blend of JP-8 and FT fuel," the AFRL engineer reported, "it sealed up again."[18] Once resolving this issue, the AFCO moved forward with B-52H testing and certification.

With eight separate engines, the B-52H was the perfect platform to lead the way through the alternative fuel certification process. First, the AFCO performed uninstalled engine ground testing in July 2006. Next, in September 2006 the first U.S. military flight powered by artificial fuel took place over Edwards AFB when the B-52H flew with the synthetic fuel blend powering two of its eight engines.[19] The team certified the B-52H after flying in December 2006 with all eight engines fueled by the synthetic blend.[20] Since the B-52H certification, the AFCO has also certified the B-1B, C-17 and F-15 and begun flight-testing the C-5, C-130, F-22, KC-135, and T-38 using the synthetic fuel blend.[21] In addition to its 2016 alternative fuel procurement goal, the USAF plans to certify its entire aircraft fleet to operate on the FT synthetic fuel blend by 2011.[22]

Fischer-Tropsch Coal-to-liquid Fuel

Even though the AFCO certification process is relatively new, the fuel used has a long history. Two German scientists Franz Fischer and Hans Tropsch first developed the FT process in the 1920s. The Nazis used the FT process to produce CTL fuel during World War II and help power the German Wehrmacht and Luftwaffe. Following the war, South Africa resurrected large-scale FT CTL fuel production in the 1950s when many oil-producing countries refused to sell oil to South Africa's apartheid regime.[23] The South African government established a state energy company, which is now the privatized company Sasol. Today, Sasol operates the world's only large-scale commercial CTL plant.[24] Sasol owns two FT CTL plants, which together are capable of producing about 140,000 barrels of fuel per day.[25] Sasol also produces an enormous amount of carbon dioxide (CO_2). For each barrel of CTL product produced, Sasol emits half a ton of CO2 into the atmosphere.[26] One of Sasol's two CTL plants alone is the world's largest single emitter of CO2 on the planet.[27]

Carbon dioxide is a byproduct of the four-step CTL production process depicted in figure 1. The CTL process begins with coal gasification which occurs when superheated steam and oxygen react with coal under moderate pressure.[28] Gasification generates CO2 and various gas molecules derived from the impurities found in coal.[29] It also produces synthesis gas, known as syngas, composed of hydrogen and carbon monoxide which is used to create various hydrocarbons.[30] Because the synthesis gas is "dirty" following gasification, the second step in the process removes the CO2 and impurities. Once the synthesis gas is clean, the third step of the process is the actual FT reaction which uses various catalysts to transform the synthesis gas into a mixture of hydrocarbons.[31] The last step of the CTL process is to separate the mixture of hydrocarbons to produce two main products: naphtha and middle distillates. Naphtha is basically a very low-grade gasoline while the middle distillates can be retail-ready diesel fuel or a combination of diesel fuel and jet fuel, depending on the process.[32]

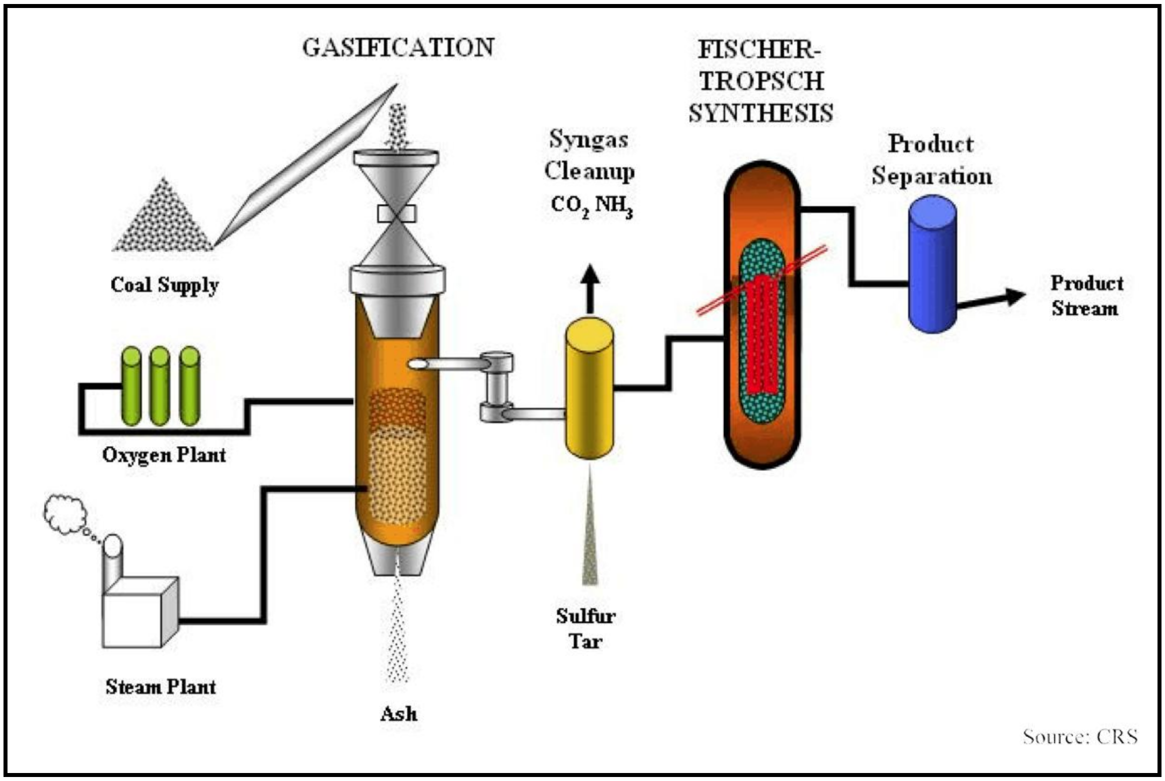

Figure 1. Coal-to-Liquid Process in a Conceptual Fischer-Tropsch Plant
(Reprinted from Andrews, "Liquid Fuels from Coal, Natural Gas, and Biomass").

At Sasol's newest, most efficient CTL plant, the process outlined above is capable of turning one ton of coal into approximately 1.2 barrels of CTL product.[33] Of that final product, about 15 percent is suitable for jet fuel.[34] So at a commercial scale, the FT CTL process turns one ton of coal into approximately eight gallons of jet fuel, among other products.[35] As previously mentioned, the resulting fuel is very clean compared to petroleum fuel. Testing performed by the AFRL found particulate emissions reduced by 50 to 97 percent when using FT fuel compared to petroleum fuel, depending on engine type and operating conditions.[36] However, the process used to produce eight gallons of jet fuel also creates half a ton of CO2, a green house gas. The United States Environmental Protection Agency estimates the life cycle green house gas emissions from FT CTL fuel to be more than twice those of similar petroleum products when no form of carbon capture and sequestration is used during CTL fuel production.[37] The disadvantage of a large carbon footprint, among others, may outweigh the benefits FT CTL fuel provides and prevent it from being a viable option with which to meet the USAF 2016 goal. On the other hand, algae-based fuels may offer an environmentally friendly solution to this goal.

Algae-based Fuel

By turning sunlight, water, nutrients and CO2 into biomass, algae offer an attractive form of renewable fuel.[38] There are many forms of algae, from seaweed to green pond scum, that grow in both marine and freshwater environments.[39] However, alternative fuel advocates are most interested in microalgae.[40] Due to their simplicity, these microscopic forms of algae are typically more efficient at turning sunlight into energy than higher order plants.[41] Algae create natural oils similar to those produced by terrestrial crops used as biodiesel feedstock, such as rapeseed and soybeans.[42] However, algae out-perform terrestrial crops in two respects. First, algae can produce up to 60 percent of their weight in the form of oils while rapeseed and soybean are composed of 40 and 20 percent oil by weight, respectively.[43] Second, in good growing conditions algae routinely double their biomass over a 24-hour period, a growth rate 30 to 100 times faster than terrestrial plants.[44] Algae's oil content and growth rate combine to produce 10 to 100 times the amount of oil per unit area of land when compared to other biofuel feedstocks.[45] A recent study out of Massey University in New Zealand highlights the main benefit of algae-based biofuels when compared to those derived from terrestrial crops. The study predicts, "between one and three percent of the total U.S. cropping area would be sufficient for producing algal biomass that satisfies 50 percent of the [United States] transport fuel needs," where as the best oil producing terrestrial crop would require 24 percent of U.S. cropland to produce the same amount of fuel.[46] Moreover, algae farms do not compete with food for cropland, as they do not require nutrient rich soil to grow. Lastly, the resultant algal oil can be refined using existing infrastructure to create products similar to those produced from crude oil, including jet fuel, diesel and gasoline.[47]

Growing algae to produce fuel is a concept that researchers have considered for over half a century. Starting in the 1950s, scientists investigated methane production from algae.[48] Within the United States the fuel crisis of the 1970s spurred renewed interest in algal fuel.[49] In 1978 the United States established what is today called the National Renewable Energy Laboratory (NREL) in the Department of Energy.[50] The NREL initiated the Aquatic Species Program (ASP) in 1978 to study the use of aquatic plants in the production of biofuels. The ASP initially investigated using algae to produce hydrogen but shifted emphasis to biodiesel production between 1980 and 1996, and thereafter lost funding.[51] While algal biofuel research slowed in the last decade, recent research has focused on the cultivation methods depicted in figure 2: the photobioreactor (PBR) and open racetrack pond.

Figure 2. Algae cultivation methods: PBR and open racetrack ponds (left to right) (Reprinted from Darzins, "Algal Biofuels Technologies").

Researchers found that both photobioreactors (PBR) and shallow open racetrack ponds are acceptable algae cultivation options.[52] Similar to typical greenhouses, PBRs are clear, closed vessels in which algae cultivate. Racetrack ponds, on the other hand, are open to the environment and use a paddle wheel to slowly stir the algae. Today, most commercial algae farms are open pond systems, because PBR equipment is much more capital intense.[53] While algae grow naturally using ambient sources of CO2, algae farms require an additional, substantial amount injected into solution in order to achieve growth rates previously discussed. Since algae require a dedicated source of CO2, most concepts place large algae farms near coal-fired power plants or some other CO2 producer.[54] Following their growth, algae are harvested using various techniques, further concentrated, and then the algal oil is extracted from the biomass.[55] Currently, there are no inexpensive ways to harvest algae and extract algal oil.[56] As an example, these two processes account for 73 percent of algal oil production costs at Solix Biofuels, a U.S.-based algae biofuel company.[57] Lastly, many burgeoning biofuel companies proffer breakthrough technologies and some even operate successful algal oil pilot projects, but, unlike Sasol's FT CTL fuel plant, no large-scale commercial algae-based fuel farm currently exists.[58] If these challenges can be overcome, the USAF may be able to reach its 2016 alternative fuel goal if it pursues algae-based jet fuel.

Literature Review

Two former Air University students Major Clinton Warner and Lieutenant Colonel Mark Danigole performed research concerning USAF alternative fuel goals and the use of FT CTL fuel and biofuels, respectively. Major Warner's research focused on the Air Force's two pronged strategy for addressing rising energy costs and increased focus on climate change prevention. Particular to this thesis, Major Warner discussed the benefits and challenges associated with FT CTL fuel and the USAF alternative fuel initiative.[59] Major Warner also provided recommendations for the Congress, DOD and USAF to bring FT CTL jet fuel into the market place.[60] However, Major Warner's recommendations were not based on any specific timeline. This paper differs from Major Warner's in that this paper investigates the likelihood a market place can be established in time to meet the USAF 2016 alternative fuels goal using FT CTL fuel.

Similarly, Colonel Danigole investigated which form of bio-jet fuel alternative would best meet President Bush's goal to "…replace more than 75 percent of our oil imports from the Middle East by 2025."[61] Colonel Danigole evaluated ethanol, terrestrial-produced biodiesel, algal oil, and bio-butanol as possible bio-jet fuel solutions.[62] Part of Colonel Danigole's analysis was to ensure each biofuel met jet fuel energy density standards, did not require any major engine modifications and met USAF fuel demand in terms of quantity, transportability and stability.[63] Colonel Danigole cited a NASA study that found operating an airplane on alcohol-based fuel would require larger wings and engines while also reducing performance when compared to an aircraft operated on jet fuel.[64] He also cited Chevron Global Aviation's description of biodiesel's cold temperature characteristics. According to Chevron, biodiesel freezes near zero degrees Celcius, which is a much higher freezing point than jet fuel's -40 degree freezing point.[65] While Colonel Danigole found ethanol, butanol and biodiesel each had limitations that did not meet his analysis criteria, he found algae-based jet fuel had no such limitations. Colonel Danigole concluded algae produced jet fuel is the preferred biofuel alternative with the potential to "…meet all USAF fuel demands by 2025."[66] This paper uses Colonel Danigole's conclusion as a starting point and assumes that algae-based jet fuel is the only feasible alternative to FT CTL fuel. However, instead of evaluating algae-based fuel's ability to meet all USAF fuel demands by 2025, this paper evaluates its ability to meet the USAF 2016 alternative fuel goal.

Evaluation Criteria

For FT CTL fuels and algae-based fuels to meet the USAF 2016 alternative fuel goal, they must have technical readiness, economic viability, minimal environmental impact and favorable political considerations. With these criteria, this evaluation assesses each fuel's ability to meet the 2016 goal. The first of these criteria consists of two parts.

The technical readiness criteria require the ability of the alternative fuel blend to substitute for petroleum-based jet fuel and provide sufficient production quantity from domestic sources by 2016. For purposes of this research, the substitute portion of technical readiness is evaluated by analyzing each alternative blend's ability to fuel aircraft engines without modification or performance degradation. The production aspect of technical readiness requires the production process to be fully developed so alternative fuel producers will be able to fulfill the quantity requirement of the USAF 2016 goal. In order to meet the USAF 2016 goal, alternative fuel must account for 25 percent of the jet fuel the USAF uses when flying in the continental United States. This equates to 400 million gallons annually and requires an alternative fuel industry that produces approximately 26,000 barrels of jet fuel per day.[67] In order to produce this amount of FT CTL jet fuel, a new plant needs to produce approximately 80,000 barrels per day of liquid products.[68] The production portion of technical readiness ties directly to the second evaluation criteria, economic viability.

For an alternative fuel to meet the USAF 2016 goal, it must be cost competitive with petroleum jet fuel. Therefore, the alternative fuel needs economic viability in order to compete with petroleum fuels. This evaluation criterion uses the projected alternative fuel production costs per barrel to predict the fuel's economic competitiveness.

After determining economic viability, the next criterion evaluated is the alternative fuel's environmental impact. This assessment explores each fuel's carbon footprint, water requirements, waste production, and jet engine emissions. Much of these environmental concerns play a large role in the last criterion, political considerations.

The last evaluation criterion assesses the political issues surrounding alternative jet fuels. As previously suggested, significant changes took place in the 2006 and 2008 elections, resulting in policy shifts. The evaluation analyzes current policy, alternative fuel subsidies and assesses political support for each fuel.

Results of Evaluation

Fischer-Tropsch Coal-to-Liquid Fuel

Based on the long history of FT CTL fuel, it is no surprise this alternative meets the technical readiness and economic viability evaluation criteria. This alternative fuel has environmentally friendly attributes and has received significant political support in the past. However, the confluence of FT CTL fuel's lifecycle green house gas emissions, current policy, and immature carbon capture and sequestration technology negatively affect this alternative's evaluation.

The technical readiness of FT CTL jet fuel is well established. For example, commercial aircraft refueling at O.R. Tambo International Airport in Johannesburg, South Africa, are just as likely to top off with an FT CTL fuel blend as they are with pure petroleum fuel.[69] Even though FT CTL fuel lacks aromatics required to prevent fuel systems from leaking, users blend the alternative with petroleum fuel to overcome this issue. By using a 50/50 fuel blend, the petroleum-based fuel provides sufficient aromatics to seal aircraft systems and requires no engine modifications. Likewise, FT CTL fuel performs almost as well as petroleum fuel. One drawback is its volumetric energy density, which is 3.7 percent lower than petroleum fuel's density.[70] This means that pure FT CTL jet fuel has less energy per gallon than petroleum jet fuel, resulting in decreased performance. However, when blended with petroleum fuel, this performance degradation is negligible.

As with its readiness to substitute for petroleum-based jet fuel, FT CTL fuel is also technically ready for production in large quantities from domestic sources. This type of synthetic fuel has been produced in large quantities since World War II. However, if the decision were made to build large-scale FT CTL fuel plants in the United States, the designs would leverage coal gasification and FT processing technology improvements currently deployed in multiple facilities around the world. Many facilities built in the last decade use efficient coal gasification techniques to create synthesis gas for chemical production or electric power generation. Future domestic CTL plants would also leverage improved FT process technologies developed by Shell, Sasol, Chevron and Exxon Mobile. Commercial natural gas-to-liquid fuel plants around the world currently use this technology. The combination of improved gasification and FT processing would nearly double the efficiency of a modern FT CTL plant over that of Sasol's plants, yielding two barrels of product per ton of coal as opposed to 1.2 barrels per ton.[71] However, some experts warn significant technical risk still exists because coal gasification and FT process improvements have never been demonstrated in an integrated FT CTL fuel production operation.[72] This technical risk must be figured into production cost predictions as it could drive up the capital investment required to build FT CTL plants in the United States. Lastly, the United States has 200 years of coal reserves with which to produce FT CTL fuel using these improved technologies. Therefore, FT CTL fuel is technically ready to both substitute for petroleum jet fuel and begin production from domestic sources using proven methods.

Not only is FT CTL jet fuel technically ready for large-scale production, it is also an economically viable alternative. Building a large-scale FT CTL fuel plant is capital intensive and the first several plants built in the United States could be more so due to technical risk. Even with this technical risk, a 2008 RAND Corporation study, sponsored by both the USAF and Department of Energy, found that an FT CTL fuel plant in the United States could be economically competitive if crude oil prices were at least $55 to $65 per barrel.[73] Similarly, a Massachusetts Institute of Technology study from 2007 predicts FT CTL fuel production costs between $50 and $55 per barrel.[74] The plant's economic viability depends in part on the rate of return investors anticipate and the type of coal used. For example, if investors require 12 percent return on investment instead of 10 percent, crude oil must be $75 per barrel vice $65 per barrel for the FT CTL fuel plant to remain competitive.[75] On the other hand, using less expensive forms of coal found in Wyoming and Montana could lower operating costs by up to $5 per barrel.[76] With crude oil prices averaging between $56 per barrel in 2005, $99 per barrel in 2008 and currently selling for over $60 per barrel, FT CTL fuel production appears economically viable.[77]

This fuel also performs well in one aspect of the environmental impact criteria. It burns more cleanly than petroleum-based jet fuel. As previously discussed, pure FT CTL fuel has almost no sulfur and no aromatics. It burns up to 97 percent cleaner than petroleum jet fuel.[78] However, the production process has multiple environmental impacts.

In order to produce FT CTL fuel in the capacities required by the USAF 2016 goal, an FT CTL fuel industry operating new plants would need 40,000 tons of coal per day or over 14 million tons per year.[79] This increase in coal demand would require the development of new mines. While coal mining is heavily regulated, there is little argument that it is a dirty endeavor with the potential to significantly impact local ecology and water quality. A few of the environmental impacts associated with coal mining are acid mine drainage, waste piles, mountain top removal, and coal dust pollution.[80] While increased coal mining has its own issues, FT CTL plants have additional environmental challenges.

Operations at an FT CTL fuel plant create additional environmental impacts such as air pollutants and potential water contamination. Coal gasification creates pollutants that affect air quality and would be regulated under current laws and regulations. Even with this regulation, the long-term effects of operating multiple CTL plants in coal producing regions could have a negative impact on air quality. Additionally, coal gasification produces solid wastes containing toxic metals and coal ash. If they are not properly disposed of, each of these byproducts can threaten water supplies. While not defined as a pollutant, FT CTL plants also produce a large amount of CO_2, a greenhouse gas.

One of FT CTL fuel's biggest hurdles is mitigating its life cycle greenhouse gas (GHG) footprint. A fuel's life cycle GHG footprint is the total quantity of GHG emissions related to all stages of fuel production, distribution and use. For FT CTL fuel, this includes the GHG emissions associated with mining and transporting coal as well as emissions from fuel production and use. Based on EPA estimates, FT CTL fuel's GHG footprint is more than twice the footprint of petroleum-based fuel.[81] Due to a Federal law passed in 2007, FT CTL fuel's GHG footprint must be addressed before the Air Force can legally procure it.

The Energy Independence and Security Act of 2007 (EISA) bans federal agencies from procuring alternative or synthetic fuels with more lifecycle GHG emissions than petroleum-based fuels.[82] While agencies can purchase small quantities for research and testing, large-scale purchases are not permitted. The EISA of 2007 restricts the Air Force from purchasing FT CTL fuel unless some form of CO_2 emission mitigation is used. There are currently two possible mitigation techniques envisioned to address FT CTL GHG emissions, but both have their own issues.

One concept reduces FT CTL fuel's lifecycle GHG emissions by mixing biomass with coal to produce synthesis gas. This technique is called coal and biomass-to-liquid

(CBTL), and it has both merits and challenges. One benefit is suitable biomass sources, such as switch grass, forest residue, corn stover and other dedicated energy crops, do not compete with food crops. Another benefit of this approach is the lifecycle GHG emissions of CBTL fuel are equivalent to petroleum-based fuel when the biomass accounts for approximately 50 percent of the feedstock.[83] In this case, about half of the CO2 released during the fuel's lifecycle is later absorbed during biomass cultivation. This results in lifecycle GHG emissions that are comparable to those of conventional petroleum fuels.[84] However, according to the RAND Corporation, "while FT CTL is commercially ready, CBTL is not."[85] Furthermore, using biomass as a feedstock increases fuel production costs. A recent National Energy Technology Laboratory study found that using as little as 30 percent biomass in FT CBTL fuel production requires oil to cost more than $100 to $120 per barrel in order for the FT CBTL fuel to be economically competitive.[86] Using 50 percent biomass reduces the economic viability of FT CBTL fuels even further. Because the CBTL approach to GHG emission mitigation is neither commercially ready nor economically viable, FT CTL fuel proponents look to carbon capture and sequestration as the path to GHG reduction.

Carbon capture and sequestration (CCS) techniques could reduce the GHG footprint of FT CTL fuel to 12% less than petroleum fuel's footprint.[87] CCS captures CO2 emissions from large producers, such as coal-fired power plants, transports the CO2 via a pipeline and stores it underground indefinitely to prevent the CO2 from reaching the atmosphere. Carbon capture during CTL production is relatively inexpensive as CO2 is already removed from synthesis gas prior to the FT reaction. However, current sequestration, or storage, technologies are immature and unlikely to be deployed on a large-scale for some time.[88] In a 2007 hearing before the Senate Energy and Natural Resources Committee, Mr. Thomas D. Shope the Acting Assistant Secretary of Energy for Fossil Energy, testified that the carbon storage technologies would not be available until after 2012 and not deployed commercially until the 2020 timeframe.[89] While proponents of FT CTL fuel point to CCS demonstration projects as proof that CCS is ready for deployment today, this is not the case. The U.S. Department of Energy's Carbon Sequestration Regional Partnership program is a research and development effort that began in 2003. It currently operates multiple small-scale CO2 storage sites and expects to begin seven large-scale field tests in 2010.[90] These tests will last between four to six years depending on the site and aim to validate regional large-scale CO2 storage capabilities. However, these projects are few in number, already have designated CO2 sources and should be in the test and validation phase come 2016.[91] Therefore, commercial carbon sequestration capability is not attainable in time to facilitate the USAF 2016 alternative fuels goal.

It is clear that FT CTL fuel meets the technical readiness and economic viability criteria. However, based on the policy shift made in the EISA of 2007, FT CTL jet fuel faces significant challenges. Coal mining and CTL production present hazards to the environment, while commercially ready carbon sequestration technologies will not be deployed by 2016. For these reasons, FT CTL fuel performs poorly against the environmental impact and political considerations criteria.

Algae-based Fuel

Algae-based fuel performs poorly where CTL shines and excels where CTL faces challenges. While algae are commercially cultivated for various products, there are no large-scale commercial farms that produce algae-based fuel. Therefore, algal fuel's technical readiness for large-scale production and economic viability are unproven. However, algae do not compete with food crops for land, they have a small GHG footprint and benefit from current Federal renewable fuel policies. Based on these considerations, algae-based fuels perform well against the environmental impact and political considerations evaluation criteria.

Algae-based jet fuel is a suitable substitute for petroleum-based jet fuel. According to the NREL, "With various hydroprocessing technologies used by refineries…, the algal oils could be made into a kerosene-like fuel very similar to petroleum-derived commercial and military jet fuels."[92] In early 2009 both Continental Airlines and Japan Airlines conducted test flights using a blend of petroleum and biofuel with a portion of the biofuel derived from algal oil. The Continental Airlines press release describing their flight, the first to use algae-derived jet fuel, explains that no modifications to the aircraft or engines were necessary and "the biofuel meets and exceeds specifications necessary for jet fuel."[93] While algae-based jet fuel is technically ready as a petroleum fuel substitute, the same cannot be said for its large-scale production readiness.

To date, algae-based fuel farms have been relatively small-scale research or demonstration projects. While several start-up biofuel companies produce algal fuel, significant production issues remain. Algae harvesting and oil extraction are currently production challenges that account for a large majority of production costs. In the draft *National Algal Biofuels Technology Roadmap*, the U.S. Department of Energy (DOE) explains breakthroughs in harvesting technology are needed to get costs under control and enable scalability.[94] Furthermore, the DOE claims that current algal oil extraction "is largely in the realm of laboratory scale processes."[95] Understandably, these immature production processes help make algae-based fuels expensive.

Several groups have studied the potential costs associated with producing algal oil. In conjunction with the ASP in the 1990s, the NREL predicted that algal oil could be produced in the range of $52 to $91 per barrel.[96] In 2004 an algal oil demonstration report projected production costs to be $84 per barrel using current technologies.[97] These two predictions are representative of several studies' conclusions that algal oil may be competitive with petroleum. However, NREL's assumptions about algae's oil yield have not yet been demonstrated.[98] The 2004 production estimate relies on algae cultivation performance demonstrated in multiple independent projects, not based on performance proven in a single pilot-plant.[99] Additionally, an Israeli company, Seambiotic, grows algal oil at a small demonstration facility with production costs of $209 per barrel on average.[100] While many studies have predicted algae-based fuel will be economically competitive, this claim remains unproven and will not be realized until breakthroughs in algal oil cultivation, harvesting and extraction occur. At the Algae World 2008 Conference, Dr. John Benemann, a former NREL researcher and principal author of the ASP final report, quantified the type of research breakthrough required. Dr. Benemann explained, "a major improvement in productivity… with a doubling, or even tripling, in outputs of what is currently possible" is required for algal oil to compete with petroleum.[101] Though algae-based jet fuel is not yet economically viable, it has many environmental benefits.

Compared to petroleum fuel, algae-based fuel emits fewer particulates, air toxins and carcinogens.[102] Additionally, algae cultivation can occur in saltwater, brackish water, wastewater, and need not compete for fresh water resources like terrestrial crops used for biofuel.[103] Most systems recycle the majority of the water used to grow algae and require only enough continuous water resources to combat evaporation from the open ponds. Algae also do not compete with food crops for land like other biofuel feedstocks. Algae absorb CO2 during cultivation, expounding the benefits of renewable fuel sources without using critical water or land resources. Every pound of algae grown removes 1.8 pounds of CO2 from the environment.[104] However, algae-based jet fuel's GHG footprint is not carbon neutral.

Algae-based fuels are lauded as a carbon neutral fuel, but this is not completely accurate. During cultivation algae absorb large amounts of CO2 then release it into the atmosphere when the algae is processed and burned as fuel. A recent study found algae-based fuels release 85 to 93 percent less lifecycle GHG emissions than petroleum fuel.[105] Unlike terrestrial biofuel crops, algae absorb only a small portion of their required CO2 from the atmosphere. Commercial-scale algae farms require dedicated CO2 sources like coal-fired power plants or other industrial suppliers to support rapid growth rates. When burning algae-based fuel, CO2 emissions are released into the atmosphere and not re-absorbed by additional algae cultivation. Therefore, algae-based fuels essentially delay the introduction of industrially produced CO2 into the atmosphere. The real GHG benefit derived from burning algae-based fuel is that it replaces petroleum fuel while making use of industrial CO2 emissions. Recently proposed legislation captures this benefit.

The American Clean Energy and Security (ACES) Act of 2009 recognizes the potential of algae-based energy. As part of the proposed GHG cap-and-trade policies, the ACES of 2009 recognizes that commercial-scale algae cultivation essentially delays the release of carbon into the atmosphere. The proposal requires either algae-based fuel producers or their industrial sources of CO2 be held accountable for algae fuel CO2 emissions.[106] While this aspect of the policy may deter algae cultivation, algae energy benefits from the legislation because it is defined as renewable biomass.[107] Under the proposal, CO2 emissions from renewable biomass are not capped when fueling power plants or other industrial GHG emitters, making algae biomass an attractive feedstock.[108] The EISA of 2007 also established policies beneficial to algae-based fuel. First, EISA adjusts the nation's renewable fuel standard and mandates increased renewable fuel production from 9 billion gallons in 2008 to 36 billion gallons in 2022.[109] Second, EISA requires advanced biofuels, which include algae-based fuels, to make up 21 billion gallons of the 2022 mandate.[110] In order to make this policy a reality, EISA increases federal funding such that biofuel subsidies will exceed $25 billion by 2022.[111] Overall, recent legislation favors advancement in renewable fuel technology and production and algae-based fuels stand to benefit from these policies.

Clearly algae-based fuel performs well under the environmental impact and political considerations criteria. However, large-scale algae cultivation methods are immature and costly. In turn, the economic viability of algal oil remains unproven. While many studies have shown algae-based fuels potential competitiveness, these predictions remain unverified. For these reasons, algae-based fuels perform poorly against the technical readiness and economic viability criteria.

Analysis of Results

Based on the evaluation results, one must conclude that the Air Force will be hard pressed to meet the 2016 alternative fuel goal. Both FT CTL and algae-based jet fuels must overcome significant challenges before either is ready to produce the large quantities required to meet the USAF goal. For FT CTL, the challenges are environmental and political. For algae-based fuel the challenges are technical and economic. However, given the movement toward renewable, environmentally friendly forms of energy, algae-based jet fuel is the stronger alternative.

Both FT CTL fuel and algae-based fuel must overcome considerable obstacles prior to commercial-scale production readiness. The obstacles for FT CTL fuel are policy driven. While FT CTL fuel is technically and economically production-ready, the EISA of 2007 prohibits government agencies from procuring this fuel due to its environmental impact. FT CTL fuel will be able to overcome this policy only when CCS is operationally deployed in the United States. Based on the DOE's own predictions, CCS will not be ready for commercial use until 2020, which, in turn, leads to the conclusion that FT CTL jet fuel will be unable to fill the USAF's 2016 requirement. Algae-based fuel has similar obstacles to overcome.

In order for algae-based jet fuel to be commercially viable, technical maturity and production costs must improve. Breakthroughs in harvesting technology and algal oil extraction are needed to get costs under control. Additionally, competitive cost predictions are based largely on unproven algal oil production output. According to Dr. Benemann, "…the development of the algal strains and cultivation technologies… required for biofuels production will be very difficult and require years…."[112] Dr. Emil

Jacobs, the vice president for research and development of Exxon Mobil, which recently invested $600 million into algae research, predicts large-scale commercial algae-based fuel plants are at least five to ten years away.[113] Therefore, algae-based jet fuel may not be ready for commercial-scale production come 2016 and unable to meet USAF needs.

Not only is the USAF 2016 alternative fuel goal aggressive given the state of alternative jet fuels, but the USAF should also consider how best to position itself for the most likely national energy policies of the future. These policies no longer focus on energy security but now renewable, environmentally friendly energy sources. Therefore, the USAF alternative fuels initiative should reconsider the focus of its effort.

In 2006 the USAF began its alternative jet fuels initiative and focused on FT CTL fuels. The next year, Congress responded by passing the EISA of 2007 and prohibited federal agencies from purchasing alternative fuels with excessive GHG emissions. In 2008 the Senate version of the National Defense Authorization Act (NDAA) for FY09 included a provision extending the DOD's contracting authority for alternative fuels from five years to ten years. Although the provision did not specify any particular alternative fuel, the Congressional Budget Office presumed DOD would use extended authority to purchase FT CTL fuel and calculated the provision would cost the government $6 billion over ten years--the cost of building an FT CTL fuel plant. Even though fuel prices reached an all-time high during bill consideration, the alternative fuel contracting authority provision was stripped from the bill during Senate and House of Representatives conference deliberations. Most recently, the Senate version of the NDAA for FY10 included an alternative aviation fuel provision codifying USAF alternative fuel goals. This provision was also stripped in conference. According to a Senate Armed

Services Committee staff member, anti-coal members of the House of Representatives eliminated the provision.[114] Even though the USAF alternative fuels initiative does not specify the type of alternative fuel being pursued, lawmakers equate USAF alternative fuels with coal and FT CTL jet fuel. In order to posture for the future, the USAF needs to shift the focus of its alternative fuel initiative away from FT CTL fuel.

While policy trends discourage the FT CTL industry, they support the pursuit of algae-based jet fuel. Not only does the EISA of 2007 prohibit federal agencies from procuring GHG intensive alternative fuels, but it also encourages renewable fuel development and production through the expanded renewable fuel standard. Additionally, proposed energy legislation, the ACES of 2009, encourages the use of renewable biomass for energy production. Both of these recent policies encourage biofuel development, including algae-based fuels. While large-scale algae cultivation is not proven to be economical, algae's potential as a biofuel cannot be ignored. Compared to terrestrial biofuel crops, algae cultivation does not compete for food cropland nor does it require significant water resources. Additionally, algae have demonstrated the ability to grow more biofuel per acre than any other crop. Despite algae-based fuel production's technical immaturity, recent policy trends combined with algae's biofuel potential demand the USAF refocus its alternative fuels initiative on algae-based jet fuel.

Recommendations

The purpose of this research was to examine current realities and determine whether the Air Force should continue focusing on FT CTL fuel or instead concentrate research, development and incentives toward algae-based fuel in order to stay on track towards its 2016 alternative fuel goal. The analysis shows that both FT CTL and algae-based fuels have technical readiness challenges that may inhibit their large-scale commercial use by 2016. Regardless, the shift in national energy policies requires the Air Force to likewise shift its alternative fuel focus to a suitable renewable source, of which algae-based jet fuel is the most promising. The following recommendations will facilitate the change in focus.

First, the Air Force should continue efforts to certify the entire aircraft fleet to operate on the FT synthetic fuel blend by 2011. Even though the AFCO is currently using FT fuel derived from natural gas, the certification process provides valuable information that will speed aircraft certification for other alternatives.[115]

Next, the Air Force needs to take action to divorce CTL fuel from the alternative fuel initiative. The national energy policy has shifted to focus on renewable forms of energy. For the Air Force to gain national policymaker's support for its alternative fuel initiative, the Air Force needs to make the shift as well. In order to successfully disassociate coal from the alternative fuel initiative, the Air Force should begin by highlighting biofuel programs it already has in place. For example, The Air Force Office of Scientific Research is currently sponsoring four academic algae-based fuel research projects.[116] Additionally, the AFCO has plans to begin testing renewable biofuels in Air Force aircraft. Officials are planning to acquire 320,000 gallons of two different types of biofuels for testing and certification between 2011 and 2013.[117] Discussing and promoting these projects would be the first step toward gaining broad support for the Air Force's alternative fuel initiative. The next step would be to consider changing the 2016 alternative fuel goal.

Air Force leadership would effectively communicate the change in focus by changing the 2016 goal. While the analysis shows alternative fuels may not be ready to fulfill the 2016 goal's requirements, the Air Force should not change this goal to a later date. Keeping the goal set at 2016 will help spur alternative fuel development and reassure producers that they have a costumer in waiting. The Air Force does, however, need to add one word to the goal – renewable – to effectively eliminate CTL as an option. The Air Force should change its 2016 goal to the following. *By 2016, the Air Force plans to cost competitively acquire 50 percent of the Air Force's domestic aviation fuel requirement via a* <u>*renewable*</u> *alternative fuel blend in which the alternative component is derived from domestic sources produced in a manner that is greener than fuels produced from conventional petroleum*. After highlighting current biofuel initiatives and updating the 2016 goal, the Air Force should urge the DOD to begin a concerted algae-based jet fuel research and development effort.

Because algae has the potential to fulfill future renewable fuel requirements, the DOD should begin a department-wide algae research and development initiative aimed at improving the commercial readiness of algae-based fuel. Multiple independent algae research and development projects are already underway. For example, the Defense Advanced Research Projects Agency, the Navy and the Air Force all have separate algae-based jet fuel programs underway. All DOD algal fuel research programs would be more effective if they collaborated and coordinated with each other. Within the DOD, the Air Force has the largest liquid fuel requirement. Therefore, the Air Force could take the lead of this joint effort, but this is certainly not a requirement. Not only should the DOD establish an integrated approach to algae-based fuel research, but the federal government should as well.

In 2003, the federal government wanted to prove the concept of clean-burning, coal-fired power plants. The DOE established the FutureGen initiative in which the government partnered with industry to build a state-of-the-art, zero-emissions electrical power plant. The results of FutureGen research and development were to be shared with all participants to include international partners and the public. By establishing a government sponsored development program, DOE hoped lessons learned from FutureGen would proliferate clean coal technology around the world. While the FutureGen project was subsequently restructured such that the project now has no chance of meeting original goals, the program's government-private structure provides an excellent model for government sponsored algae-based fuel research and development.[118]

In order to accelerate research and development required to bring algae-based fuels to market, DOE should establish, and Congress should support, an algae initiative similar in concept to FutureGen. Under this concept, DOE would partner with private industry to research, develop and build a commercial-scale algal oil production farm. In order to attract private partners, the government would share project costs and risks. The public would benefit by ensuring the technological breakthroughs discovered become public information rather than the intellectual property of a private company. Under this program, the successful algae cultivation techniques and methods developed could be highly proliferated to rapidly establish an algae-based fuel industry. Incorporating these recommendations at the Air Force, DOD and national level will help ensure commercially available algae-based jet fuel becomes a reality.

Conclusion

Based on the current state of alternative fuels technology, the Air Force will likely be unable to meet its 2016 alternative fuels goal. FT CTL fuel itself is a technically ready and economically viable alternative. However, the FT CTL fuel industry is dependent on CCS deployment in order to limit GHG emissions. Because widespread CCS deployment is not expected until 2020, FT CTL fuel will not be able to meet the Air Force's 2016 alternative fuel goal. Similarly, algae-based fuel is still in the research and development phase and not ready for commercial-scale production. Technological breakthroughs are required in order to make economically viable algae-based jet fuel a reality. Some predict the industry requires five to ten more years of research before algae-based fuel will be commercially viable. Therefore, it is unlikely algae-based jet fuel will be able to meet the Air Force's 2016 goal. However, policy trends require the Air Force shift its alternative jet fuel focus from FT CTL to algae-based fuels.

Since 2007, a series of policy changes reveal a shift in national energy policy from one of energy security to one focused on clean, renewable forms of energy. The EISA of 2007 not only prevents federal agencies from procuring alternative fuels with greater GHG emissions that petroleum fuel, but the law also establishes an aggressive national renewable fuel standard. Added to this, energy derived from biomass would further benefit from current proposals being considered by Congress. In order to posture for the future, the Air Force must adapt current initiatives and align them with the national policy shift toward renewable forms of energy. If the Air Force has any chance of reaching its 2016 alternative fuel goal, it must refocus its efforts from FT CTL fuel to the most promising renewable alternative, algae-based jet fuel. By changing the focus of its alternative fuel initiative, the Air Force will gain the support of national policymakers and posture the alternative aviation fuel initiative for future success.

Notes

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6 . Dreazen, "U.S. Military Launches Alternative-Fuel Push."
7 . Billings, address, Air Force Association Convention.
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30. Ibid.
31. Ibid, 17.
32. Ibid.
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34. Brown, "Air Force to Wall Street."
35. A barrel of fuel is the equivalent of 42 gallons. So, 1.2 barrels is 50.4 gallons. Fifteen percent of 50.4 is 7.56, or about eight gallons.
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38. Edwards, *Green Algae Strategy*, 4.
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